

Effects of Logging Wounds on Caucasian Alder Trees (*Alnus subcordata* C.A. Mey.) in Iranian Caspian Forests

Farzam Tavankar, Mehrdad Nikooy, Rodolfo Picchio, Amireslam Bonyad, Rachele Venanzi

Abstract

Caucasian alder is a large tree and one of the commercial species in the Caspian forests. We investigated the wound healing rate (WHR) and compared the diameter growth (DG) of 66 wounded and 66 unwounded alder trees 15 years after selected logging in these forests. The conditions of the wounds after 15 years were as follows: 56.1% had closed, 25.7% were open, and 18.2% had decayed. The mean WHR was 4.95 cm²/yr, ranging between 0 and 17.3 cm²/yr, and DG of wounded trees was 13.3% lower than in unwounded trees. The WHR and DG were related to the size, intensity and location of the wound, stem diameter (diameter at breast height; DBH), and ratio of wound size to stem basal area. The WHR in middle-aged trees was more than in young and older trees. The reduction in DG of wounded alder trees was only observed in the DBH range below 58 cm. Wounds that were larger than 100 cm² in area significantly reduced diameter growth of alder trees. Height of wound from ground level had significant negative effects on WHR and DG. Closed wounds had no significant effect on DG, but open or decayed wounds reduced DG by 13.8% and 34.3%, respectively. 72.7% of total logging wounds were caused by skidding operations where 20.8% of them were decayed, and reduced DG by 12.2%. Selective logging needs more careful planning of roads, skid trails, and winching corridors.

Keywords: Alder tree, Caspian forests, logging wound, selection cutting, wound occlusion

1. Introduction

Logging damage to residual trees during selection cutting may lead to serious economic losses in terms of timber quality at the final harvest (Kiser 2011), wood losses of damaged trees, and tree growth reduction (Vasiliauskas 2001). A number of residual trees are damaged during each selective logging operation in forests (Camp 2002, Picchio et al. 2012, Tavankar et al. 2015a). The Iranian Caspian (also called Hyrcanian) forests are managed as a mixed uneven aged high forest with single and group selective cutting regime.

Tree wounding is the most common type of logging damage, representing more than 90% of the total damage (Marchi et al. 2014, Tavankar et al. 2013). Frequency of wounded trees and intensity of wounds during logging operations can have detrimental im-

pacts on stand growth and forest sustainability. This depends on several factors such as: logging system (Bragg et al. 1994, Spinelli et al. 2010, Marchi et al. 2014), logging machines (Han and Kellogg 2000), logging season (Limbeck-Lilienau 2003), skill of workers (Wallentin 2007, Nikooy et al. 2010), harvest intensity (Fjeld and Granhus 1998, Gullison and Hardner 1993, Behjo 2014, Tavankar et al. 2015a), ground slope (Tavankar et al. 2015a), stand density (Picchio et al. 2012), and design of the extraction trails (Gullison and Hardner 1993, Nikooy et al. 2012, Danilović et al. 2015).

Logging wounds may decrease the quality of residual trees and increase stand mortality through insect and disease infestation (Han and Kellogg 2000). Wounding can cause stem deformities and significant losses of the final crop volume and value (Meadows 1993, Lo Monaco et al. 2015). Logging wounds on re-

sidual trees often become an input port for fungal decay (Vasiliauskas 2001), especially in wounds that are near the ground level or root wounds (Bettinger and Kellogg 1993, Camp 2002).

The ability of trees in occlusion of their logging wounds, not only depends on the time elapsed from wound occurrence, it also depends on the site conditions, tree species, tree age, and wound characteristics (Vasiliauskas 2001, Tavankar et al. 2015b). Normally, the required time for healing of logging wounds in fast-growing tree species is lower than in slow-growing tree species (Vasiliauskas and Stenlid 2007). Wound characteristics such as size, location, and intensity are the main factors in wound-healing ability and diameter growth of trees (Tavankar et al. 2015b). Wounding season was also reported as another factor that has effects on wound healing (Limbeck-Lilienau 2003). The amount of decayed logging wounds decreased as the wound height increased (Han et al. 2000).

Safeguard ecological and production aspects of forest ecosystems, such as this studied, can result in limiting logging damages to residual trees. This must remain a major objective in selection managing of forests, because the quality of timber starts in the forest.

In the Iranian Caspian forest, the future of logging wounds and the effect of wounds on diameter growth of alder trees is unclear. In order to improve logging methods, more knowledge about the long term impact of forest operations is needed (Whitman et al. 1997, Tavankar and Bonyad 2014). The objectives of this study were to:

- ⇒ study the characteristics of logging wounds in alder trees
- ⇒ investigate healing rate of logging wounds in alder trees over a period of 15 years after logging damage
- ⇒ investigate the effect of logging wounds on diameter growth of alder trees
- ⇒ find some possible relations between wound characteristics (size, location, and intensity), healing rate and diameter growth of alder trees.

2. Materials and methods

2.1 Study area

This study was conducted in the Caspian forests of Iran. These forests are located in the north of the country in south coast of the Caspian Sea, extending from the coastal area to an elevation of 2800 m on the northern aspects of the Alborz mountain belt, and cover an

area of about 2 million hectares (Poorzadi and Bakhtiari 2009). The Iranian Caspian forests are rich in biodiversity, and include a lot of stand types and about 80 woody species (Marvie-Mohadjer 2006). These forests are natural and broadleaf. Moreover, they are the only commercial forests in Iran.

The study area is located in four adjacent parcels in district 1 of the Asalem Nav watershed in the Iranian Caspian forests. The Nav watershed is located between 37°38'34" to 37°42'21"N and 48°48'44" to 48°52'30"E. Elevation in the study area ranged from 950 to 1430 m a.s.l. The average rainfall ranged from 920 to 1250 mm per year, with the heaviest precipitation in summer and fall. The average daily temperature ranges from a few degrees below 0°C in December, January, and February, and up to +25°C during summer. The soil of the study site is classified as a brown forest (*Alfisols*) and well-drained. The texture of the soil ranges from clay loam to loamy. The original vegetation of this area is an uneven-aged mixed forest dominated by *Fagus orientalis* Lipsky (55%) and *Carpinus betulus* L. (28%), with the companion species *Alnus subcordata* C.A. May (8%), *Acer platanoides* L. (4%), *Acer cappadocicum* Gled. (3%), *Ulmus glabra* Huds. (1%), and *Tilia begonifolia* Steven (1%) (Tavankar et al. 2015b).

In these forests, selective cutting is the most common silvicultural method. Harvest trees were marked before the cutting operation in July 1999. During December 1999 and January 2000, the marked harvest trees, scattered in the study area, were felled, bucked and topped by chain saw, at a merchantable height or 20 cm diameter under bark (DUB). During April and May 2000, logs were winched from the felling site (downhill) to the back of a skidder on a skid trail (uphill) by cable of the skidder winch. In the final phase of primary transportation, logs were skidded to roadside landings by a Timber-jack 450 C wheeled skidder. The mass of the skidder was 9.8 t, and its width and length were 3.8 and 6.4 m, respectively. The harvesting system was the cut to (commercial) length by ground-based skidding. In particular, timber was extracted mostly in logs of long-length (7.8 m), or seldom in logs of short-length (5.2 m). The DBH of harvested trees ranged between 20 and 135 cm, with an average of 68.2 cm. The skidder drive was limited to the constructed skid trails. The skid trails were planed and constructed before the felling season. The skidder group included a driver, a chaser, and a feller. The winching operation was controlled manually. Tree density, stand basal area, and growing stock above 10 cm diameter at breast height (DBH) before and after selective cutting are shown in Table 1.

Table 1 Main dendrometric parameters of the stand before and after selective cutting treatment

Stand	Before cutting	After cutting	Harvested
Density, stem/ha	270.4	255.2	15.2
Basal area, m ² /ha	27.3	23.0	4.3
Volume, m ³ /ha	205.7	182.9	22.8

2.2 Data collection and analysis

Immediately after logging (year 2000), damage caused by mechanical means to residual trees was assessed by systematic sample plots. The grid dimensions were 100×100 m and the plot area was circular at 0.1 ha, and all wounded alder trees (83 stems) were identified, numbered and marked. The position of each damaged tree was also identified on a topographical map using the global positioning system (GPS). The following parameters were recorded for each wounded tree: DBH and diameter at wound height (DWH) measured by dendrometric caliper in mm; wound intensity (i.e. type of damaged tissues: bark, phloem, and wood fibers); cause of wounding (i.e., felling or winching); and the location and size of the wounds. The cause of wound was determined on the basis of wound characteristics such as position, size, type (horizontal or parallel) and intensity. The wound size was determined by measuring the maximum length and width with a ruler (to a ±0.5 mm accuracy) and calculating the ellipsoid surface area (Picchio et al. 2011). Wound sizes were then classified into 4 classes: <25, 25–100, 100–200, and >200 cm². The position of the wound (average height from the ground) was determined with a tape measuring the distance between the wound center and the ground. The location of the wounds was recorded in 3 classes, <0.3, 0.3–1, and >1 m (Limbeck-Lilenau 2003, Nikooy et al. 2010). Near to each wounded tree, an unwounded alder with similar characteristics (i.e. DBH, height, vitality, crown class of all the trees: i.e. dominant, co-dominant, subdominant, etc.) was selected and measured, as a control tree. After 15 years (in 2015), 66 pair of trees (wounded and control trees) were identified in the study area. The DBH and condition of wounds were reexamined and classified in three types: closed, open and decayed (Han et al. 2000, Tavankar et al. 2015b). The 15 year period diameter growth of wounded and unwounded trees was calculated using Eq. 1 (Clark and Clark 1992). Reduction of diameter growth was calculated using Eq. 2, wound healing rate (WHR), and the ratio of wound size to stem basal area (RSA)

at wound occurrence time (in 2000) were calculated using Eq. 3 and Eq. 4, respectively.

$$DG = \frac{DBH_2 - DBH_1}{t} \quad (1)$$

$$RDG = \frac{UDG - WDG}{UDG} \quad (2)$$

$$WHR = \frac{WS_1 - WS_2}{t} \quad (3)$$

$$RSA = \frac{WS}{SBA} \quad (4)$$

Where:

DG diameter growth, mm/yr

DBH₁ diameter at breast height at the start of interval, mm

DBH₂ diameter at breast height at the end of interval, mm

t time interval between two measurements, years

RDG reduction of diameter growth

UDG unwounded diameter growth

WDG wounded diameter growth

WHR wound healing rate, cm²/yr

WS₁ wound size at the start of interval, cm²

WS₂ wound size at the end of interval, cm²

WS wound size, cm²

SBA stem basal area, cm²

After checking for normality (Kolmogorov-Smirnov test) and homogeneity of variance (Levene test), paired *t*-test was applied to compare means of DG in wounded and unwounded trees. ANOVA and Duncan tests were used for the effect of wound characteristics on WHR and DG. A nonparametric Chi-squared test of contingency tables was applied to determine whether significant differences existed among the number of each wound condition (closed, open, and decayed) and wound intensities (bark, phloem, and wood) for different wound characteristics (Eq. 5). Tests were not conducted if the expected frequency in any cell of the contingency table was <5.

$$X^2 = \sum_{i=1}^k \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \quad (5)$$

Where:

O_{ij} sample number of the *i*th row and the *j*th column in the contingency table

E_{ij} theoretical number of the *i*th row and the *j*th column in the contingency table, and the degree of freedom, *df* = (*k* – 1) × (*r* – 1)

Regression analysis was applied to test the following relations between:

Table 2 Main average wound characteristics (mean \pm SD) referred to year 2000 and statistical analysis results. The data were detailed for cause and reported also in total

Cause of wounds	n	Wound size, cm ² *	Wound height, m *	Wound intensity		
				Bark, %	Phloem, %	Wood, %
Felling	18	200.9 \pm 172.4 ^a	1.61 \pm 0.84 ^a	33.3	44.5	22.2
Skidding	48	55.7 \pm 48.5 ^b	0.29 \pm 0.11 ^b	2.1	25.0	72.9
Total	66	95.3 \pm 103.3	0.65 \pm 0.44	10.6	30.3	59.1

* Difference letters in columns indicate significant differences between the means at $\alpha < 0.05$ by Duncan test

\Rightarrow DG and DBH for both damaged and undamaged trees

\Rightarrow DG and RSA

\Rightarrow WHR and RSA

\Rightarrow WHR and DBH

\Rightarrow WHR and DG.

All analyses were performed using SPSS 19 (IBM, NY, USA).

3. Results

These wounded alder trees constituted 18.3% of the residual alder trees and 1.54% of the total residual trees in the sample plots. 27.3% of total logging wounds were caused by the felling operation and 72.7% were caused by the skidding operation (Table 2). The mean size and height of felling wounds were significantly greater ($p < 0.01$) than those of skidding wounds. The percentage of intensive wounds by winching operation was more than the percentage of intensive wounds by felling operation, so 12 wounds (25%) of all winching wounds occurred with phloem-damaged intensity, 35 wounds (72.9%) occurred with wood-damaged intensity, and only one wound occurred with bark-damaged intensity. About a third of all felling wounds (33.3%) occurred with bark-damaged intensity, 8 wounds occurred with phloem-damaged intensity, and only four wounds (22.2%) occurred with wood-damaged intensity.

The frequency of wounds for DBH classes by cause of wound is shown in Table 3. From the analysis of all the wounds, 7.6% were found on trees with DBH < 20 cm, 34.8% on trees with DBH ranging from 20 to 40 cm, 33.3% on trees with DBH ranging from 40 to 60 cm, 15.2% on trees with DBH ranging from 60 to 80 cm, and 9.1% on trees with DBH > 80 cm. In each DBH class the frequency of skidding wounds was higher than the frequency of felling wounds.

Results of the secondary assessment (in 2015) showed that 56.1% of the wound had closed, 25.7%

were open, and 18.2% of the wound had decayed (Table 4).

The results of ANOVA tests showed that the wounds condition had significant effects on the WHR ($F=292.9$; $P < 0.001$) and WDG ($F=9.6$; $P < 0.001$). The average WHR in closed wounds was significantly greater ($p < 0.01$) than the average WHR in open and decayed wounds. The average of unwounded diameter growth (UWDG; control trees) was estimated to 6.48 \pm 1.6 mm/yr, and the average of wounded diameter growth (WDG) was 5.62 \pm 1.70 mm/yr (a reduction of 13.3%). Paired samples t -test indicated that there were no significant differences between DG of wounded and unwounded alder trees, but DG of decayed wounds was significantly lower than the DG of unwounded alder trees.

Wound conditions (2015) in relation to wound characteristics (2000) are shown in Table 5. The highest percentages of closed wounds were observed for wounds < 25 cm² (81.8%), wounds with a bark-damaged intensity (100%), wounds on the stem > 1 m (88.9%), and wounds from the felling (61.1%). The highest percentages of open wounds were observed in the wounds > 200 cm² (50%), and the highest percentages of decayed wounds were observed in the wounds of 100–200 cm² (44.4%).

The Chi-squared tests showed that the wound size, and wound intensity had significant effects on wound conditions ($p < 0.01$). The wound location

Table 3 Absolute and percentage wound frequencies for each DBH class by cause of wound

Cause of wound	DBH, cm								
	<20		20–40		40–60		60–80		>80
	n	%	n	%	n	%	n	%	
Felling	2	40.0	7	30.4	4	18.2	3	30.0	2
Skidding	3	60.0	16	69.6	18	81.8	7	70.0	4

Table 4 Averages (\pm SD) of wound healing rate (WHR), wounded diameter growth (WDG) and reduction in diameter growth (RDG) for each wound condition referred to year 2015 and statistical analysis results. The data were detailed for typology of wound condition and reported also in total

Wound condition	Frequency		WHR*	WDG*	RDG
	n	%	cm ² /yr	mm/yr	%
Closed	37	56.1	8.3 \pm 2.8 ^a	6.5 \pm 0.9 ^a	0.3 \pm 0.1
Open	17	25.7	1.2 \pm 0.3 ^b	5.6 \pm 1.1 ^b	13.8 \pm 3.4
Decayed	12	18.2	0.3 \pm 0.1 ^b	4.3 \pm 1.1 ^{c**}	34.3 \pm 8.0
Total	66	100	4.95 \pm 3.23	5.62 \pm 1.70	13.3 \pm 5.2

** Significant difference with the mean diameter growth of unwounded trees at $\alpha < 0.01$ by paired *t* test

* Difference letters in columns indicate significant differences between the means at $\alpha < 0.05$ by Duncan test

(height from ground level) had also significant effects on wound conditions ($p < 0.05$), but the cause of wounds had no significant effect on wound conditions.

The highest wound healing rate (WHR) was observed in the wounds with a bark-damaged intensity (10.32 cm²/yr), and the lowest wound healing rate was observed in the wounds > 200 cm². The ANOVA tests showed that all independent variables (size, intensity, location and cause of wounds) had significant effects on WHR ($p < 0.01$). With the increase of wound size and wound intensity, WHR decreased, but with the increase of wound height from ground level, WHR increased.

The highest percentages of reduction in diameter growth (RDG) were observed in the wounds > 200 cm² (22.6%), wounds with a damaged wood intensity (11.7%), wounds at < 0.3 m (14.4%), and wounds from the skidding agent (12.2%). The results of paired samples *t* test showed that the average of diameter growth in wounded trees (WDG) with wound sizes of 100–200 cm² (5.52 mm/yr, RDG=14.8%) was significantly lower ($p < 0.01$) than the diameter growth of unwounded trees (UWDG=6.48 mm/yr). The results of paired samples *t* tests also indicated that the average values of diameter growth in wounded trees with wounds > 200 cm² (5.01 mm/yr, RDG=22.6%), phloem (5.83 mm/yr, RDG=10.1%), and wood intensities (5.72 mm/yr, RDG=11.7%), in heights < 0.3 m (5.55 mm/yr, RDG=14.4%), and wounds from skidding agents (5.69 mm/yr, RDG=12.2%) were significantly lower than the diameter growth of unwounded trees. However, diameter growth of wounded trees

with wounds < 25 cm² (6.33 mm/yr, RDG=2.3%), bark intensity (6.44 mm/yr, RDG=0.6%), position 0.3–1 m (6.3 mm/yr, RDG=2.7%), position > 1 m (6.39 mm/yr, RDG=1.4%), and wounds from felling agents (6.23 mm/yr, RDG=3.9%) have no significant difference compared to the average of UWDG.

The regression analyses showed that: the wound healing rate (WHR) decreased by increasing the ratio of wound size to basal area (Fig. 1); trees with DBH of 40–60 cm had the highest WHR (Fig. 2); the WHR increased by increasing diameter growth of alder trees (Fig. 3); growth of wounded and unwounded trees was similar when DBH was greater than 58 cm (Fig. 4); diameter growth decreased by increasing ratio of wound size to basal area (Fig 5).

Table 5 Wound conditions (2015) in relation to wound characteristics (2000) and statistical analysis results. The data were detailed for wound size, intensity, position and cause

Wounds in year 2000		Wound conditions in year 2015			Chi-squared	WHR* cm ² /yr
Characteristics	n	Closed %	Open %	Decayed %		
Size, cm ²					155.9**	
< 25	11	81.8	18.2	–		8.13 ^a
25–100	31	74.2	19.3	6.5		6.81 ^a
100–200	18	22.2	33.3	44.4		1.45 ^b
> 200	6	16.7	50.0	33.3		1.01 ^b
Intensity					98.2**	
Bark	7	100	–	–		10.32 ^a
Phloem	20	75.0	20.0	5.0		7.16 ^b
Wood	39	38.5	33.3	28.2		3.00 ^c
Height from ground level, m					43.8**	
< 0.3	42	47.6	31.0	21.4		3.69 ^c
0.3–1	15	60.0	20.0	20.0		5.88 ^b
> 1	9	88.9	11.1	–		9.94 ^a
Cause of wound					3.7	
Felling	18	61.1	27.8	11.1		9.84 ^a
Skidding	48	54.2	25.0	20.8		3.24 ^b

** Significant difference with the mean diameter growth of unwounded trees at $\alpha < 0.01$ by Chi-squared test

* Difference letters in columns indicate significant differences between the means at $\alpha < 0.05$ by Duncan test

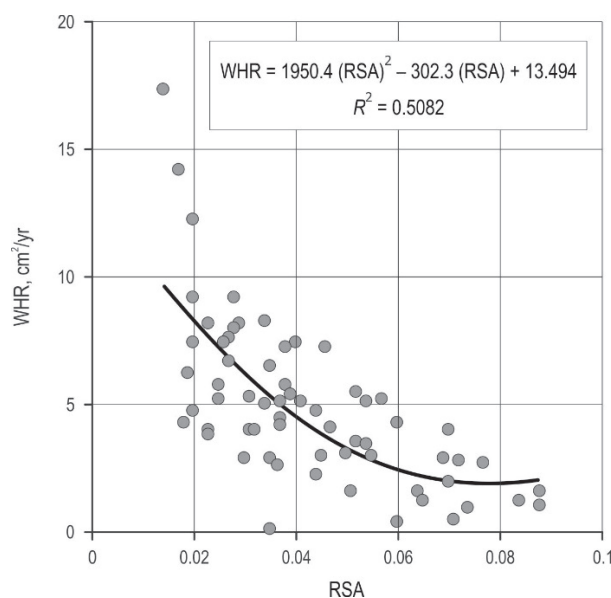


Fig. 1 Non-linear regression of wound healing rate (WHR) in relation to the ratio of wound size to basal area (RSA) of alder trees, detailed statistical results shown in Table 6

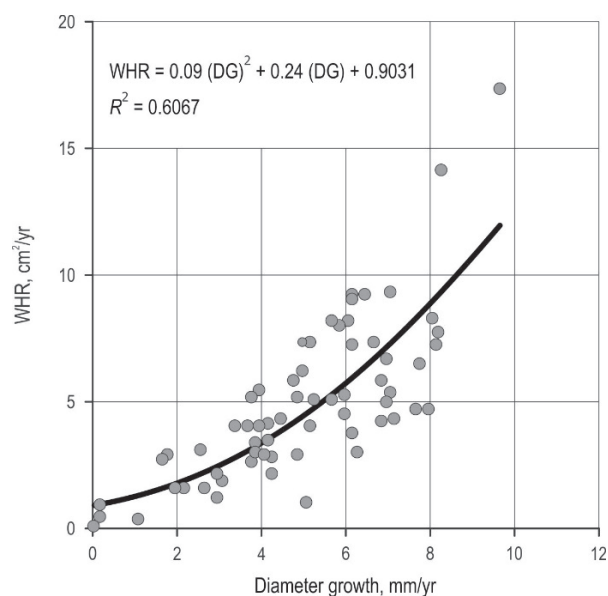


Fig. 3 Non-linear regression of wound healing rate (WHR) in relation to diameter growth of alder trees, detailed statistical results shown in Table 6

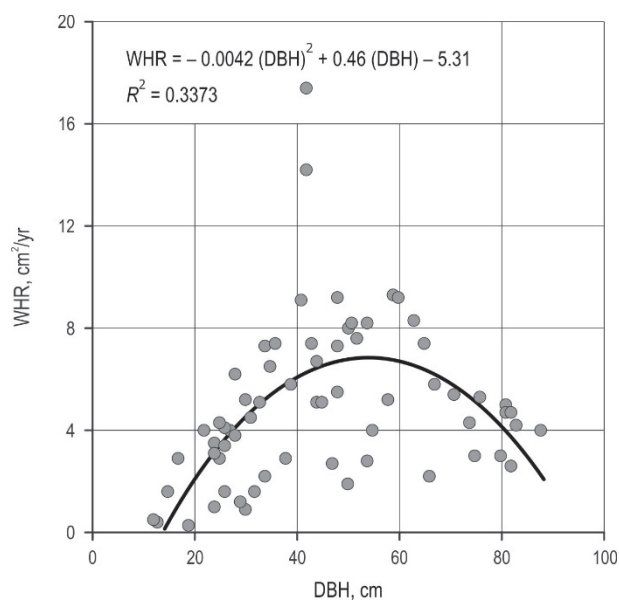


Fig. 2 Non-linear regression of wound healing rate (WHR) in relation to DBH of alder trees, detailed statistical results shown in Table 6

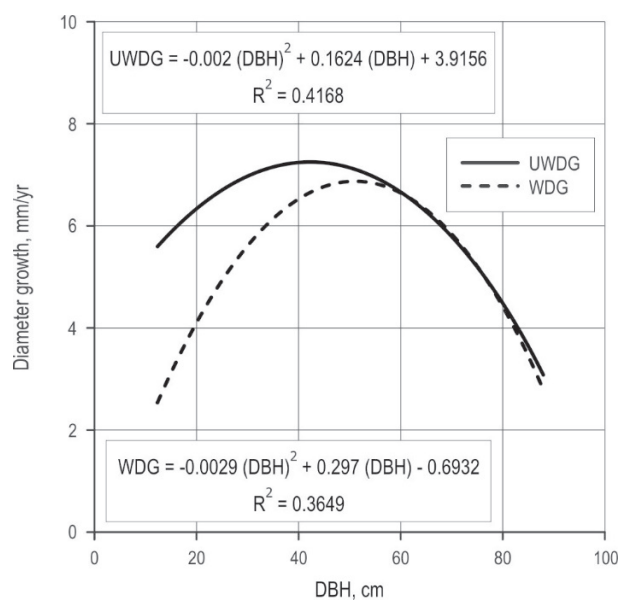


Fig. 4 Non-linear regressions of annual diameter growth of wounded (WDG) and unwounded (UWDG) alder trees and their DBH, detailed statistical results shown in Table 6

4. Discussion

4.1. Logging wounds

The results showed that 18.3% of residual alder trees sustained damage. This amount of damage was more than the amount of damage to all residual tree

species (8.4%). This is probably in response to the position of alder trees in forest stands, which is closer to disturbed areas such as roads and skid trails (Tavankar et al. 2015a).

About 86% of these wounds were situated on the bottom 1 m of the stem and about 73% were caused by

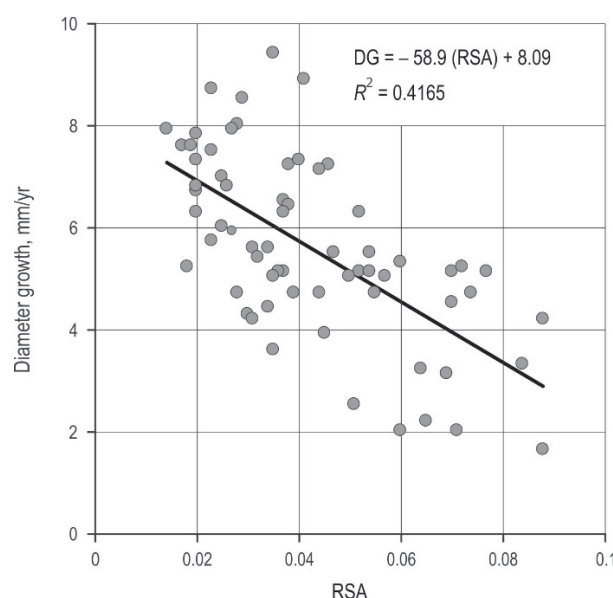


Fig. 5 Linear regression of diameter growth (DG) and ratio of wound size to basal area (RSA), detailed statistical results shown in Table 6

log winching in accordance with the results of other studies (Vasiliauskas 1993, Froese and Han 2006, Naghdi et al. 2008, Kosir 2008, Nikooy et al. 2010, Picchio et al. 2012, Marchi et al. 2014, Tavankar et al. 2013, Lotfalian et al. 2008, Majnounian et al. 2009, Jourgholami 2012, Tavankar et al. 2015a). In particular, the bottom 1 m of the stem represents the most valuable part of the tree and also the most vulnerable part to biological diseases; indeed, it was there that the highest percentage of open and decayed wounds occurred.

Most damage occurred in DBH classes of 21–40 and 41–60 cm, 34.8% and 15.2%, respectively. As

shown for beech trees in uneven aged forests (Tavankar et al. 2015a), wounded trees are mostly distributed in the two central DBH classes. The probability of damage depends on the felling intensity and trees density (Picchio et al. 2012), for the typical structure of the uneven aged forest (groups of coetaneous trees), and correct silvicultural treatment, similar to a thinning (more intensive in the central DBH classes).

Pre-harvest planning and winching path marking before logging operations can reduce damage to the stand in these forests. Whereas residually damaged trees were highly concentrated near the skid trails as shown in other studies (Naghdi et al. 2009, Ezzati and Najafi 2010), skid trail planning before felling operations can substantially reduce the skidding damage (Naghdi et al. 2008, Majnounian et al. 2009). Nikooy et al. (2010) reported that skilled operation of a skidder can decrease the level of damage. Picchio et al. (2012) studied improved winching techniques designed to decrease stand damage in the forests of central Italy. They reported that the use of a snatch block decreased by one-quarter the frequency of wounded trees from 50% to 36%. Han and Kellogg (2000) suggested that artificial tree protection rigging such as rub pads should be used to prevent damage on stumps and stems. Therefore, training of forest workers and adequate technologies can be effective in reducing logging damage on residual stands. All workers should be made aware of the purpose of the selection cutting and both the minor and major injuries to the residual stands as well as excessive ground disturbance, which may result in significant volume losses (Davis and Nyland 1991) and the natural regeneration of the forest (Picchio et al. 2012). Limiting logging damage to residual trees must remain a major objective in selection managing of forests (Tavankar et al. 2015a).

4.2. Wound healing

The mean wound healing rate (WHR) was 4.95 cm²/yr, ranging between 0 and 17.3 cm²/yr, and depended on wound characteristics (size, intensity, and location), tree age, and ratio of wound size to stem basal area (RSA).

After 15 years from the occurrence of wounds, 51.1% were closed. In this case, unlike what was observed in similar conditions for beech trees (37.5% closed after 10 years from wound occurrence) (Tavankar et al. 2015b), alder seems to react in a better way in recovering from the wounds, especially wounds caused by skidding impact.

The results showed that WHR decreased by increasing wound size and wound intensity, and increased by the increasing height of wound from ground level.

Table 6 Detailed results of regression analysis showed in Fig. 1–5 for relationship between: wound healing rate (WHR) and ratio of wound size to basal area (RSA), WHR and diameter at breast height (DBH), WHR and diameter growth (DG), wounded diameter growth (WDG) and DBH, unwounded diameter growth (UWDG) and DBH, diameter growth (DG) and RSA in alder trees

Variables	N	r ²	r ² adjusted	SE	F	p-value
WHR–RSA	66	0.508	0.493	2.30	32.55	<0.001
WHR–DBH	66	0.337	0.316	2.66	16.03	<0.001
WHR–DG	66	0.607	0.594	2.05	48.59	<0.001
WDG–DBH	66	0.365	0.345	1.60	46.53	<0.001
UWDG–DBH	66	0.417	0.398	1.23	22.51	<0.001
DG–RSA	66	0.417	0.407	1.36	45.69	<0.001

The mean WHR of felling wounds (9.84 cm²/yr) was significantly higher than the WHR of skidding wounds (3.24 cm²/yr). This is due to the position and intensity of skidding wounds. For the extraction wounds, normally the first meter of the stem was damaged and the wounds were large and deep, extending below the bark down into the wood. These are ideal conditions for infection caused by diseases, in particular fungi.

The highest coefficient of determination was found between diameter growth and WHR (Adj. $r^2 = 0.59$).

4.3. Diameter growth

Diameter growth (DG) of wounded alder trees (5.62 mm/yr) was 13.3% lower than that of unwounded alder trees (6.48 mm/yr). Tavankar et al. (2015b) studied the effects of logging wounds on diameter growth of beech trees (*Fagus orientalis*) in Caspian forests and reported a reduction of 8.1%.

The reduction in diameter growth of wounded trees was closely related to the wound size, intensity and location, DBH and ratio of wound size to basal area. Wounds greater than 100 cm² significantly reduced DG. Phloem and damaged wood wounds significantly decreased DG (10.1% and 11.7%, respectively). Skidding wounds significantly decreased DG (12.2%), because these wounds were intensive. The effect of wounds on the reduction of DG in the young trees was more intense than in the older trees, so the DG of wounded trees with DBH > 58 cm was equal to the DG of unwounded trees.

5. Conclusion

In the Caspian forests, the future of logging wounds and the effects of wounds on diameter growth of alder trees are unclear. This study shows how logging wounds could cause a sensitive reduction (13%) in diameter growth. Our results showed that the effect of bole wounds on the diameter growth depends on their severity, location, size, and tree age. Young alder trees were more sensitive to logging wounds. Residual stand damage is an unavoidable risk of selection cutting, but the level of damage should be minimized to assure the quality of the product in the future. The results of this study also indicate that tree skidding has a high potential for residual stand damage, and that intensive wounds occurred during skidding operations. Results show that the percentage of wounds by log skidding was higher than the percentage by tree felling (73% vs. 27%). The wound size by log extraction was smaller than by tree felling (57 vs. 201 cm²), but

the percentage of intensive wounds by log extraction was higher than by tree felling (73% vs. 22%). For these reasons it is important to minimize damage, both to the number of trees damaged and the extent of damage to the individual tree. Logging workers must be persuaded, through adequate training, that most damage to residual trees is unnecessary and avoidable.

6. References

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Authors' address:

Assist. prof. Farzam Tavankar, PhD.*
e-mail: tavankar@aukh.ac.ir
Islamic Azad University
Department of Forestry
Khalkhal
IRAN

Assist. prof. Mehrdad Nikooy, PhD.
e-mail: nikooy@guilan.ac.ir
Prof. Amireslam Bonyad, PhD.
e-mail: bonyad@guilan.ac.ir
University of Guilan
Faculty of Natural Resources
Somehsara
IRAN

Prof. Rodolfo Picchio, PhD.
e-mail: r.picchio@unitus.it
Rachele Venanzi, PhD.
e-mail: venanzi@unitus.it
University of Tuscia
Department of Agriculture and Forests Science
Via S. Camillo de Lellis
01100 Viterbo
ITALY

* Corresponding author

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